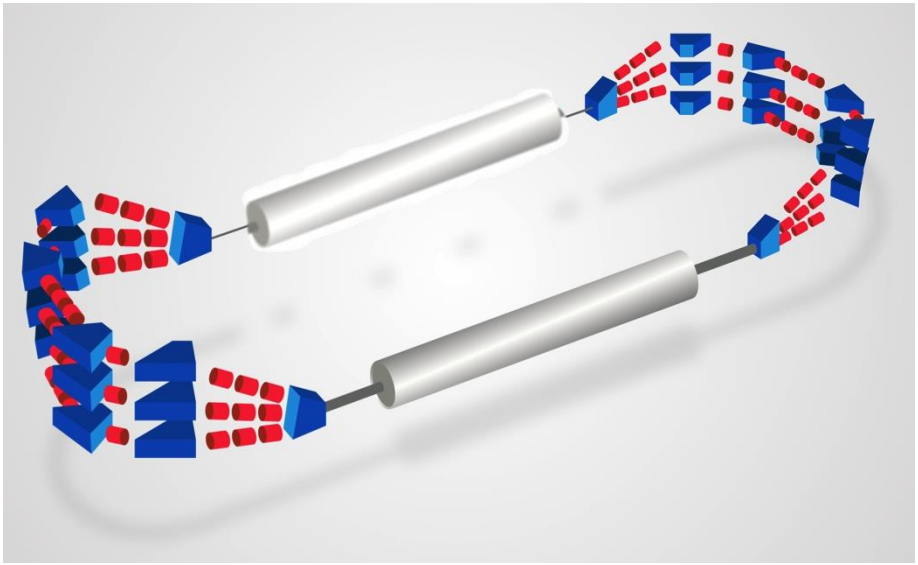
on possible nuclear-physics avenues offered by a Orsay-hosted 450-MeV PERLE version

David Verney, IPN Orsay

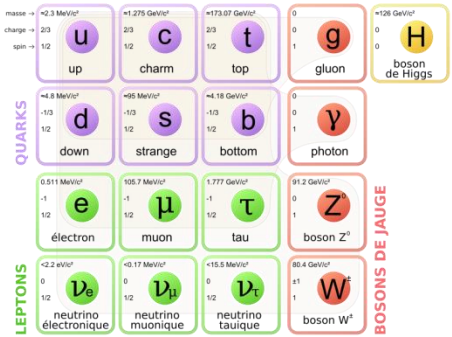


An unconventional (and somewhat provocative) introduction

The untold legend of the human quest for ultimate components of matter

The outermost Aristotle's sphere
"The final cause, then, produces motion by being loved, but all other things move by being moved"
Aristotle Metaphysics 1072b4

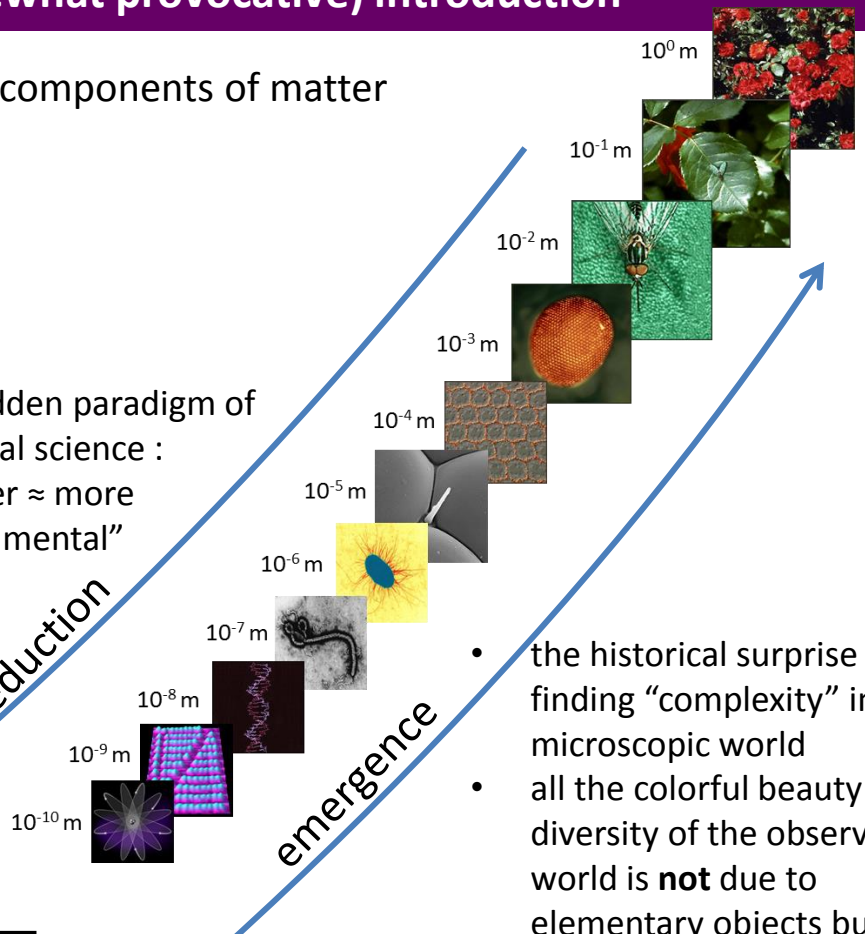
SU(3)×SU(2)×U(1)

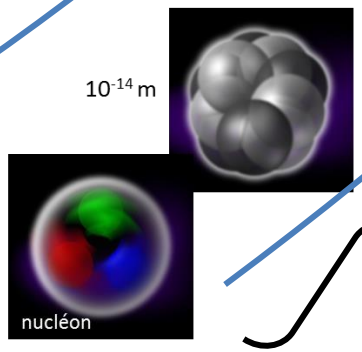


the hidden paradigm of material science : smaller ≈ more "fundamental"

reduction

emergence





- the historical surprise of finding "complexity" in the microscopic world
- all the colorful beauty and diversity of the observable world is **not** due to elementary objects but to **medium effects**

some foolish people remained stuck at this reputed unessential level of organization of matter
why ?

emergence
(presently addressed through effective theories)

The "single-particle" concept

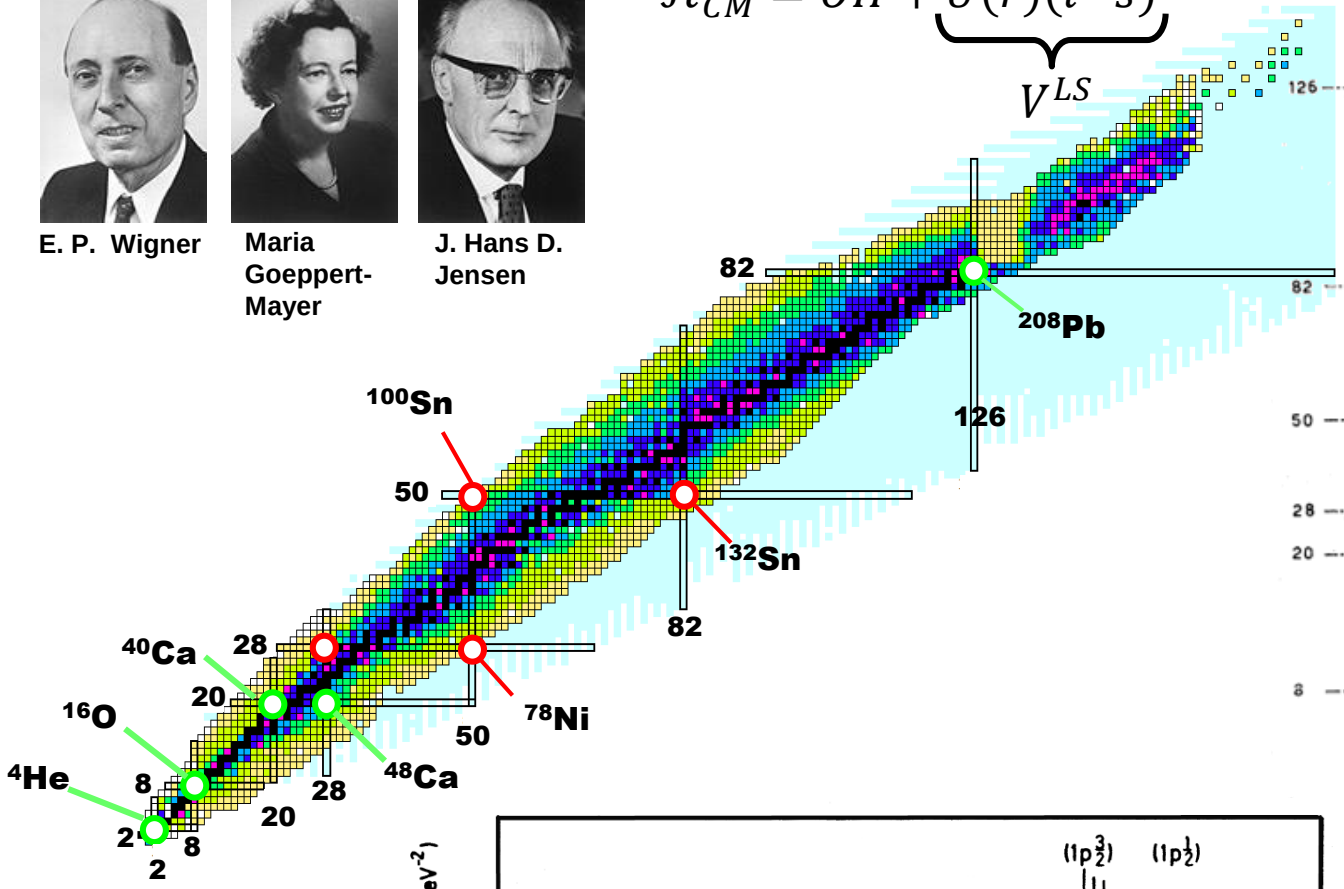
Nobel price 1963

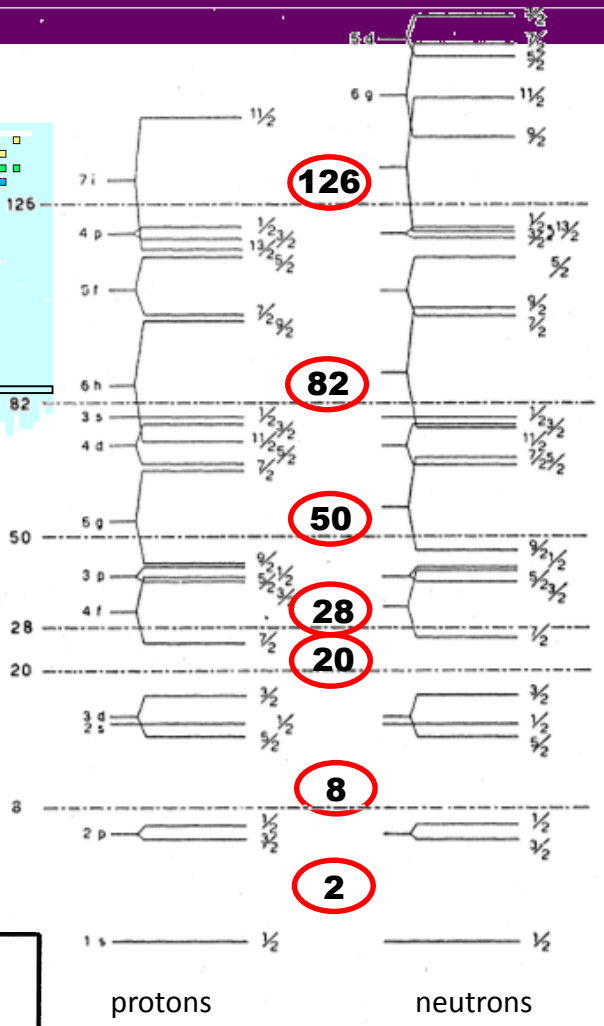
E. P. Wigner

Maria Goeppert-Mayer

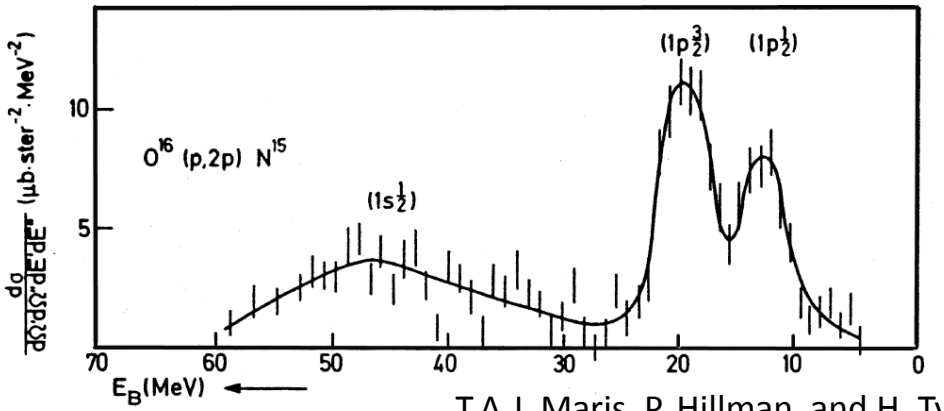
J. Hans D. Jensen

$$\mathcal{H}_{CM} = OH + \underbrace{U(r)(\vec{l}\cdot\vec{s})}_{V^{LS}}$$





cross sections



T.A.J. Maris, P. Hillman, and H. Tyren, Nucl. Phys. 7 (1958) 1.

Nobel price 1963

E. P. Wigner

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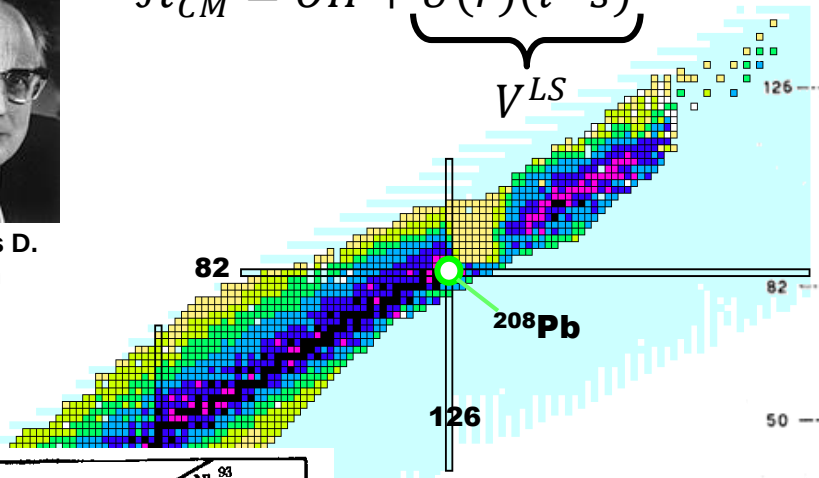
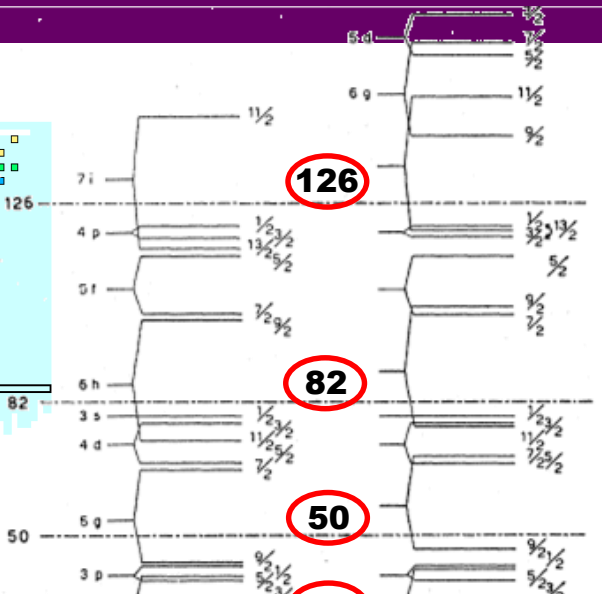
J. Hans D. Jensen

$$\mathcal{H}_{CM} = OH + \underbrace{U(r)(\vec{l}\cdot\vec{s})}_{V^{LS}}$$





magnetic moments

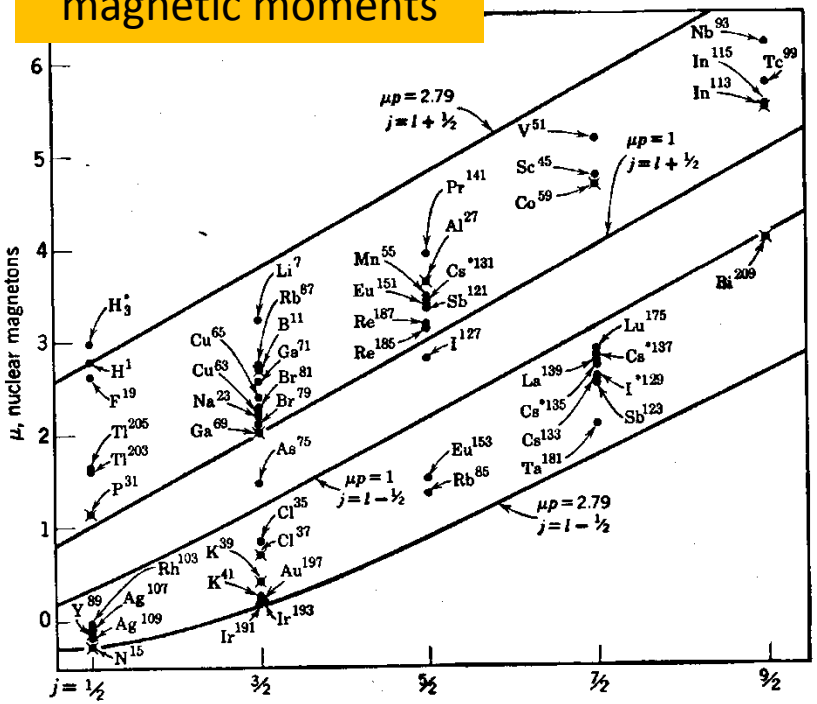


Fig. I.4. Magnetic moments of nuclei with odd Z plotted against the spin.

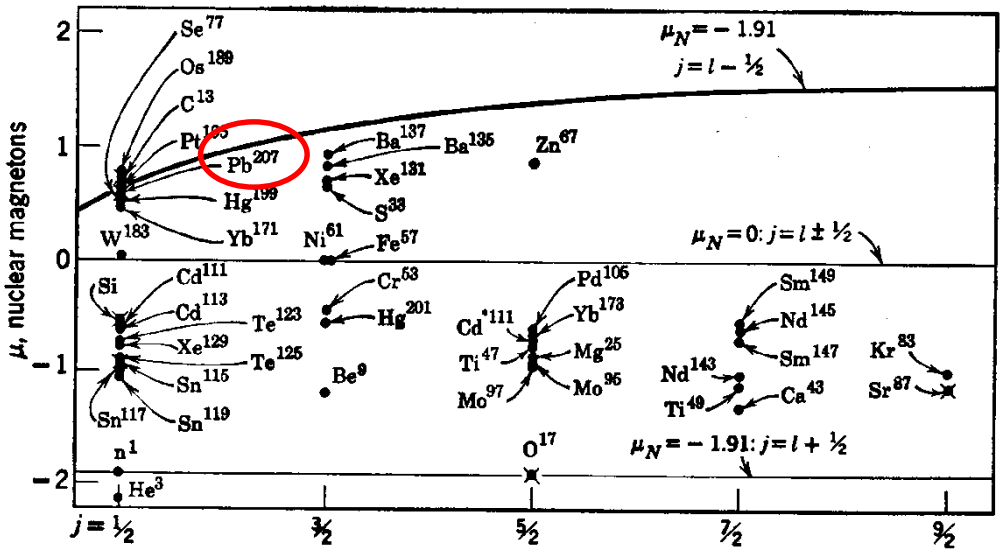


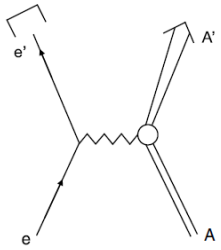
Fig. I.5. Magnetic moments of nuclei with odd N plotted against the spin.

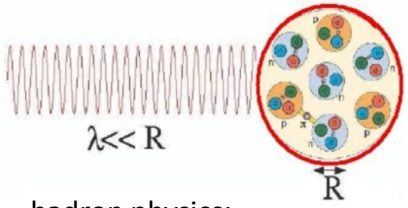
Schmidt lines

Mayer et Jensen Elementary theory of nuclear shell structure

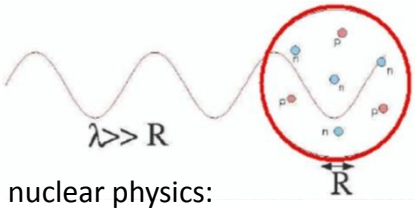
The e-probe revolution

e momentum transfer $q \approx 1/\lambda$





hadron physics:
structure of the nucleon



nuclear physics:
internal structure of the nucleus
E_e= 500 MeV → ≈0.5 fm scale

The **interior** of the nucleus became accessible !

A(e,e) elastic cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{eA\to eA} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{1+\frac{2E}{M}\sin^2(\theta/2)} |F(\vec{q})|^2$$

$$F(\vec{q}) = \frac{1}{Ze}\int \varrho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3r$$

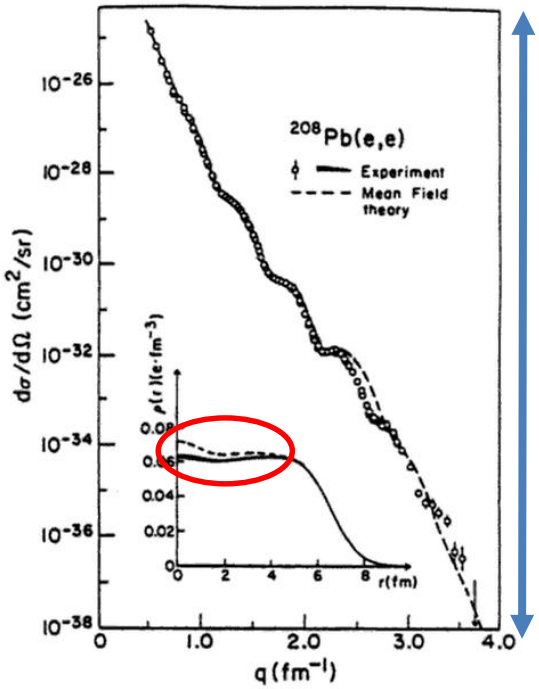
form factor

Fourier transform

point charge nucleus

$$\varrho(\vec{r}) = \frac{Ze}{(2\pi)^3}\int F(\vec{q}) e^{-i\vec{q}\cdot\vec{r}} d^3q$$

charge distribution



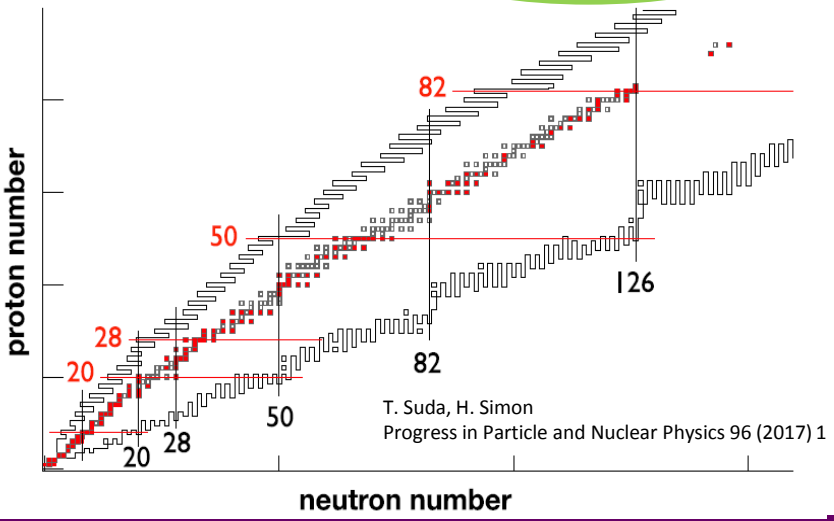
12 orders of magnitude !

B. Frois and Papanicolas
Ann. Rev. Nucl. Part. Sci 37 (1987)

Dechargé and Gogny
PRC 81 (1980)

Cavedon, Frois, Goutte et al.
PRL 49 (1982)

etc...



T. Suda, H. Simon
Progress in Particle and Nuclear Physics 96 (2017) 1

A(e,e') **inelastic** cross section

$$\frac{d\sigma}{d\Omega} = \sigma_p \eta \left[\sum_{\lambda=0}^{\infty} \frac{q_\mu^4}{q^4} |F_\lambda^C(q)|^2 + \left(\frac{q_\mu^2}{2q^2} + \tan^2 \frac{\theta}{2} \right) \sum_{\lambda=1}^{\infty} \{ |F_\lambda^E(q)|^2 + |F_\lambda^M(q)|^2 \} \right]$$

point charge nucleus

recoil factor

longitudinal form factor

transverse form factor

$$\rho_\lambda(r) = \int \langle \psi_f \| \rho_{op}(\mathbf{r}) Y_\lambda(\hat{\mathbf{r}}) \| \psi_i \rangle \, d\hat{r}$$

charge transition density

$$J_{\lambda\lambda'}(r) = \frac{i}{c} \int \langle \psi_f \| \mathbf{J}_{op}(\mathbf{r}) \cdot \mathbf{Y}_{\lambda\lambda'1}(\hat{\mathbf{r}}) \| \psi_i \rangle \, d\hat{r}$$

current transition density

$$B(\mathrm{E}\lambda) = \frac{2J_f + 1}{2J_i + 1} \left[\int_0^\infty \rho_\lambda(r) r^{\lambda+2} dr \right]^2$$

$$B(\mathrm{M}\lambda) = \frac{\lambda}{\lambda+1} \frac{2J_f + 1}{2J_i + 1} \left[\int_0^\infty J_{\lambda\lambda}(r) r^{\lambda+2} dr \right]^2$$

$\mu \approx F_M$ for $q \to 0$ (elastic at 180°)

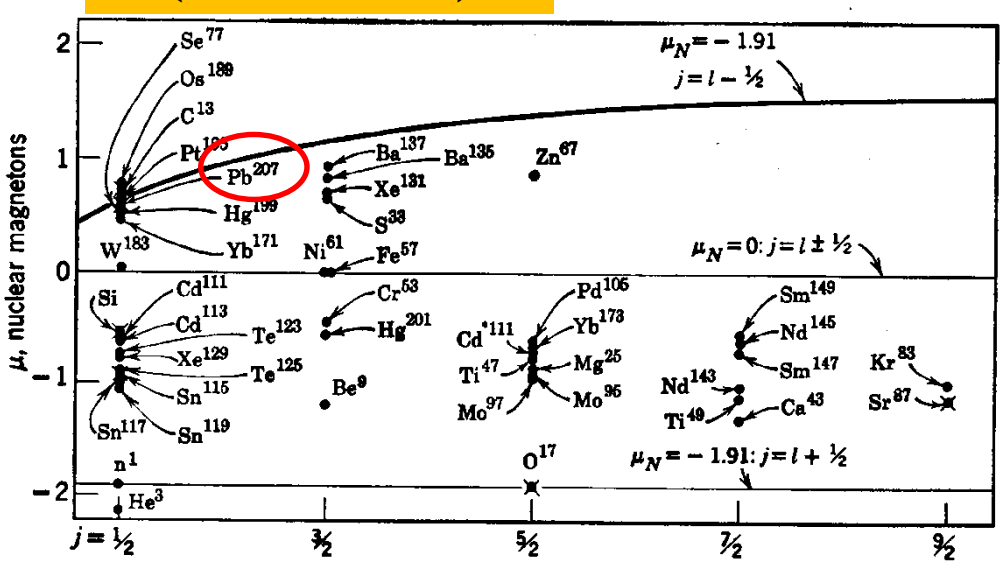
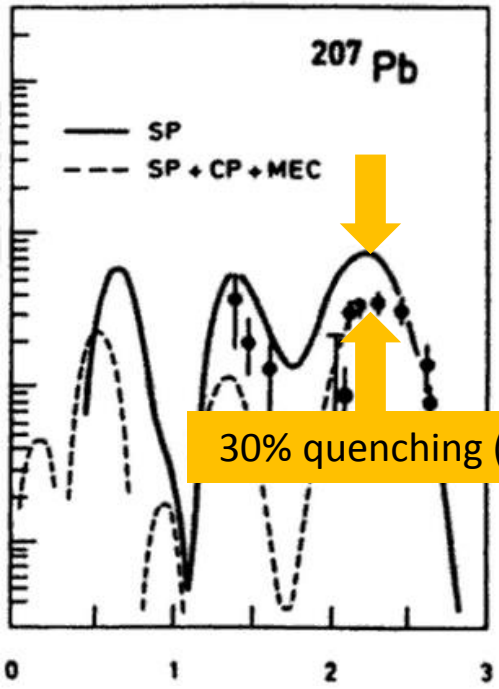


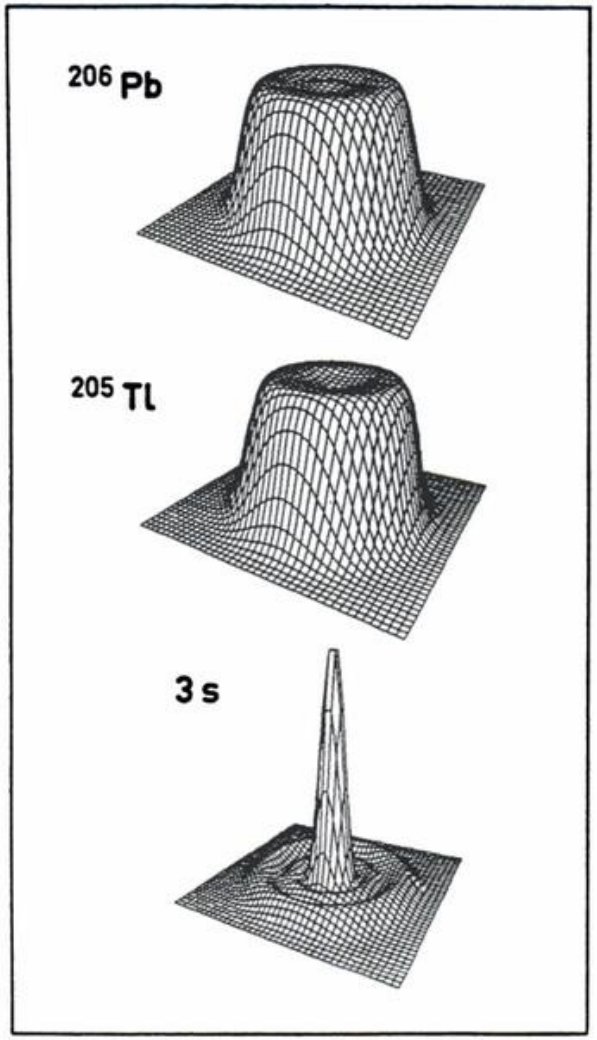
Fig. I.5. Magnetic moments of nuclei with odd N plotted against the spin.



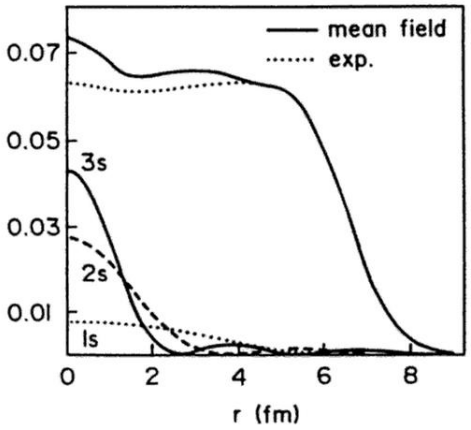
30% quenching (again!)

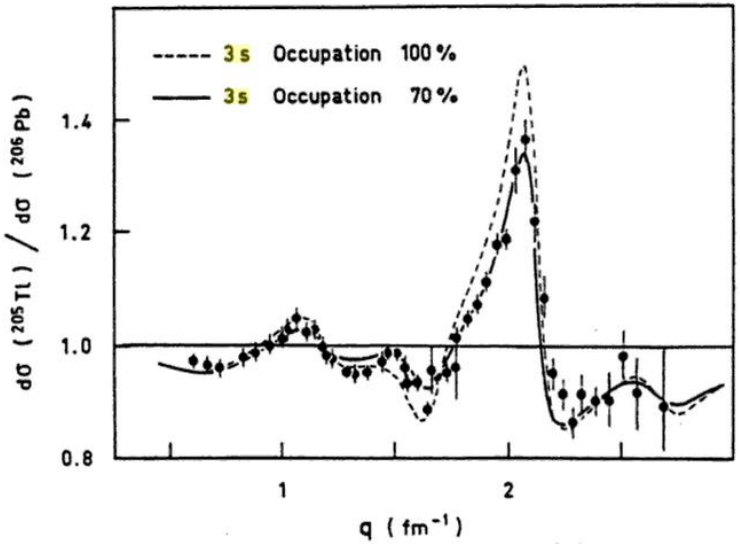
The e-probe revolution

First “picture” of a “single particle” evolving inside the nucleus



B. Frois et al
in Modern Topics in Electron Scattering
(World Scientific 1991)





could be revealed only with high q transfers
(higher sensitivity to the most inner parts of the charge distribution)

revealed **in medium effects**
(how far a “single particle” is from a free nucleon)

- part of the single-particle quenching has “trivial” origins: core (collective) couplings, many-body correlations

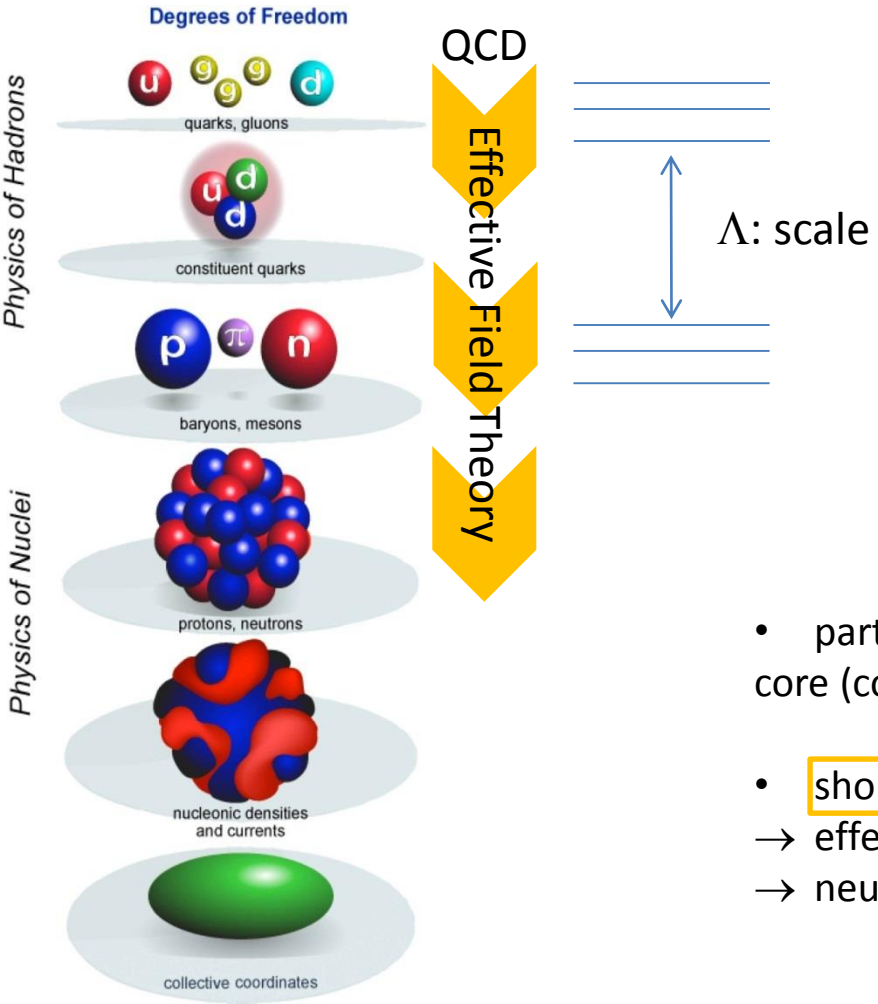
- short-range correlations, non-local part of the potential

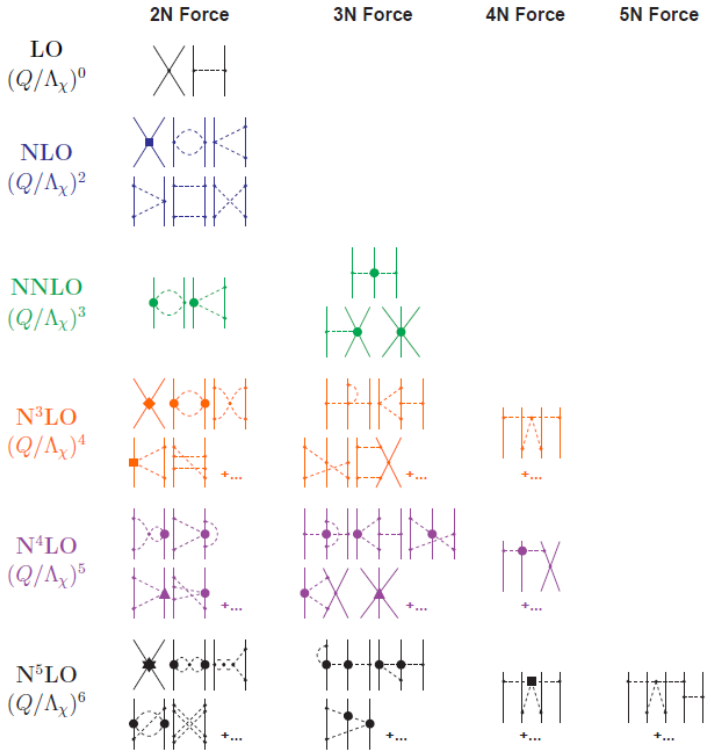
→ effective mass of the nucleon,

→ neutron skin and giant haloes formation

The e-probe revolution

First “picture” of a “single particle” evolving inside the nucleus





- part of the single-particle quenching has “trivial” origins: core (collective) couplings, many-body correlations

- short-range correlations, non-local part of the potential

→ effective mass of the nucleon,

→ neutron skin and giant haloes formation

Far from stability → (hot) example : bubble nuclei

ARTICLES
PUBLISHED ONLINE: 24 OCTOBER 2016 | DOI: 10.1038/NPHYS3916
nature physics

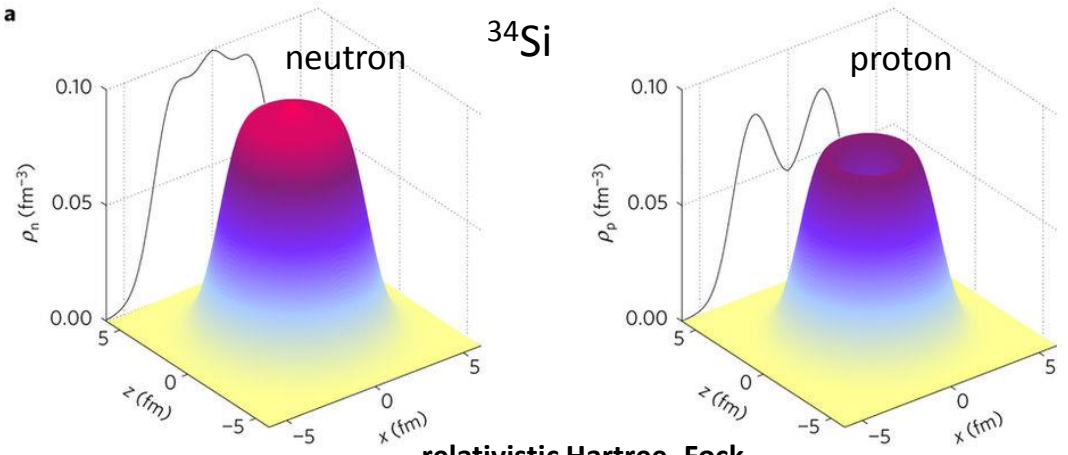
A proton density bubble in the doubly magic ^{34}Si nucleus

A. Mutschler[1,2], A. Lemasson[2,3], O. Sorlin[2]*, D. Bazin[4], C. Borcea[5], R. Borcea[5], Z. Dombrádi[6], J.-P. Ebran[7], A. Gade[4], H. Iwasaki[4], E. Khan[1], A. Lepailleur[2], F. Recchia[3], T. Roger[2], F. Rotaru[5], D. Sohler[6], M. Stanoiu[5], S. R. Stroberg[4,8], J. A. Tostevin[9], M. Vandebrouck[1], D. Weisshaar[3] and K. Wimmer[3,10,11]

PHYSICAL REVIEW C **95**, 034319 (2017)

Ab initio calculation of the potential bubble nucleus ^{34}Si

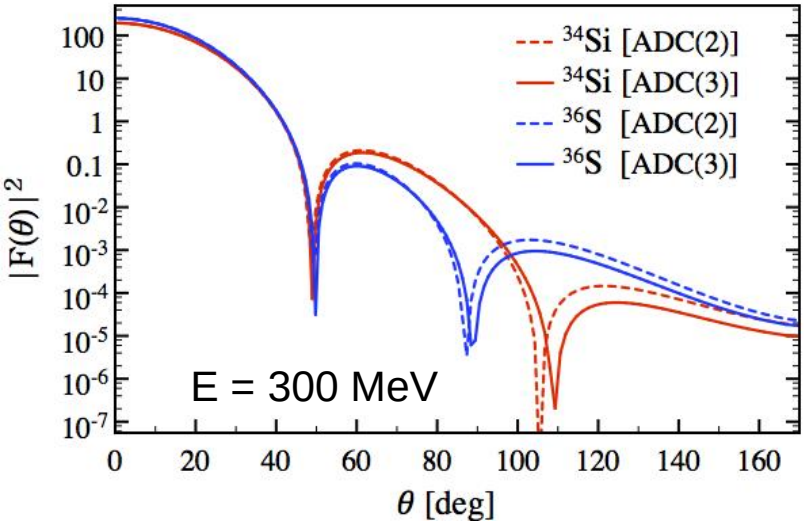
T. Duguet,[1,2,3,*] V. Somà,[1,†] S. Lecluse,[2,‡] C. Barbieri,[4,§] and P. Navrátil[5,‖]
[1]*IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*
[2]*KU Leuven, Instituut voor Kern- en Stralingsfysica, 3001 Leuven, Belgium*
[3]*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom*
[5]*TRIUMF, 4004 Westbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
(Received 25 November 2016; published 23 March 2017)



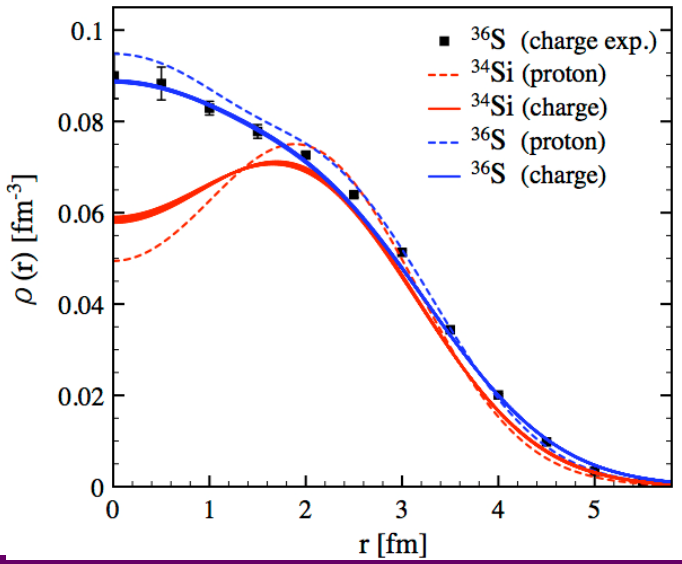
relativistic Hartree–Fock–Bogoliubov calculations

VS

ab-initio calculations



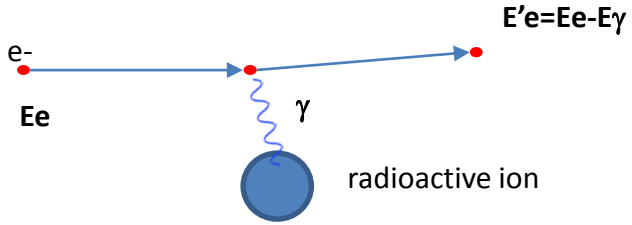
Central depletion reflects in larger $|F(\theta)|^2$ for angles $60° < \theta < 90°$ and shifted 2nd minimum by 20°



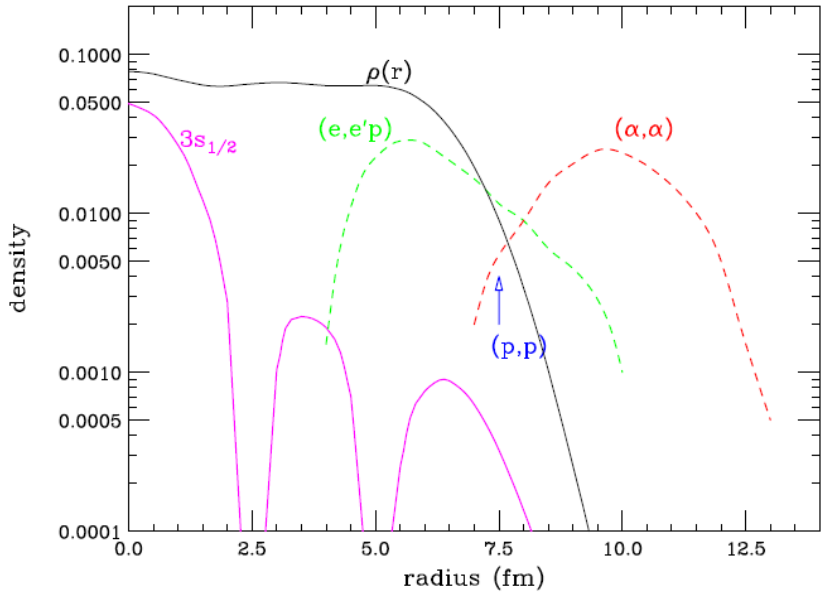
electron diffusion off RIB : a vast program

not to mention :

- perfect coulomb excitation : forward electron scattering (no multi-step process)



- clean single nucleon knock-out (quasi-free)



- Excitation of collective modes (PDR etc)

- fission studies (condition on electron energy would give precise information of the initial condition of the fissioning system)

The possible physics program spans exactly the physics interests of the vast majority of the low-energy nuclear physics community in Orsay-Saclay (and in France)
… **with a much more powerful probe**!

electron/RIB beams requirements

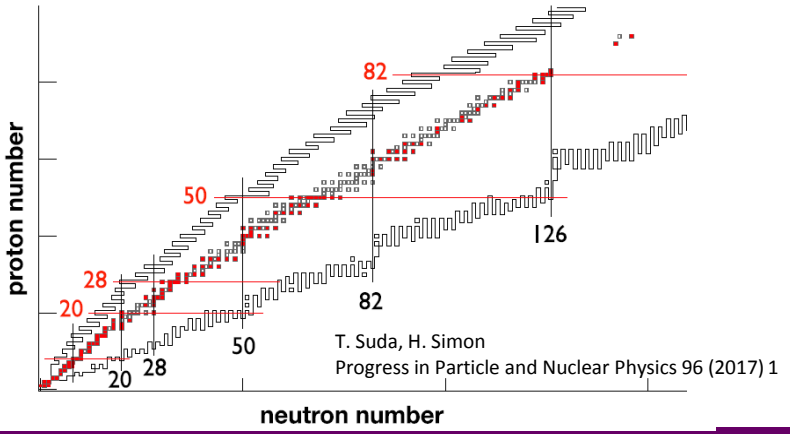
- all interesting phenomena occur at q $\gtrsim$ 2fm^{-1} ; the higher the q transferred the lower the cross section; consider previous achievements in this domain $\Rightarrow$ compromise $\boldsymbol{E_e \simeq 500\,\mathrm{MeV}}$

- Luminosity : $$L = F_e n_e \frac{N_e N_A}{4\pi\sigma_x\sigma_y} = \frac{I_e\, N_A}{4\,\pi\,\sigma_x\,\sigma_y\,q_e}$$

$\Rightarrow$ **the aimed luminosity should be 10^{29} cm^{-2}s^{-1}**
but much can be already done at $\mathcal{L} \simeq 10^{28}$ (with unstable nuclei EVERYTHING is new !)

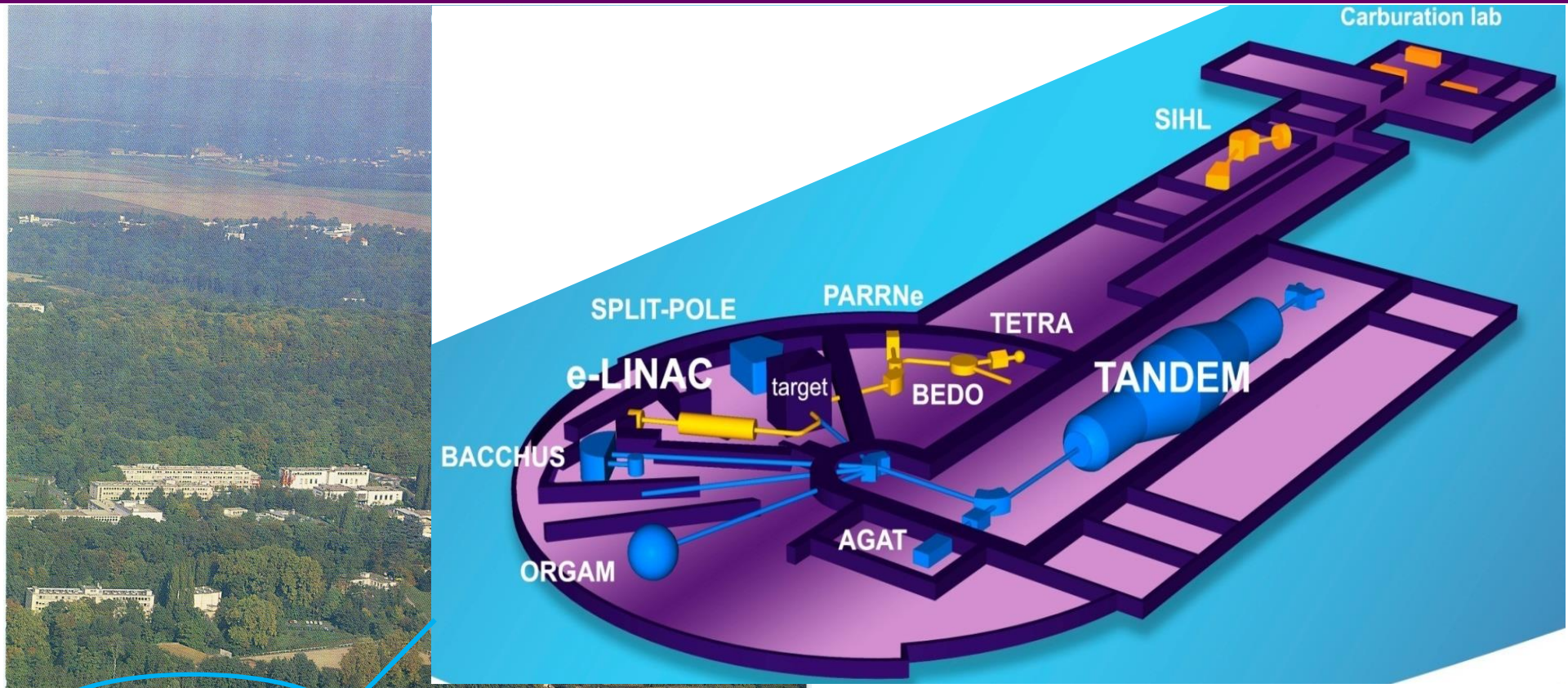
Reaction	Deduced quantity	Type	Luminosity [cm^{-2}s^{-1}]
Elastic scattering at small q	r.m.s. charge radii	Light	10^{24}
First minimum in elastic form factor	Density distribution with 2 parameters	Light Medium Heavy	10^{28} 10^{26} 10^{24}
Second minimum in elastic form factor	Density distribution with 3 parameters	Medium Heavy	10^{29} 10^{26}
Pygmy/Giant resonances	Position, width, strength, decays	Medium Heavy	10^{28} 10^{28}
Quasi-elastic scattering	SF, spectral strength	Light	10^{29}

- **strategy: fixed target $\rightarrow$ trapped RI population 10^6-10^8**



T. Suda, H. Simon
Progress in Particle and Nuclear Physics 96 (2017) 1

Beams available today at ALTO – 0.5 kW primary e-beam

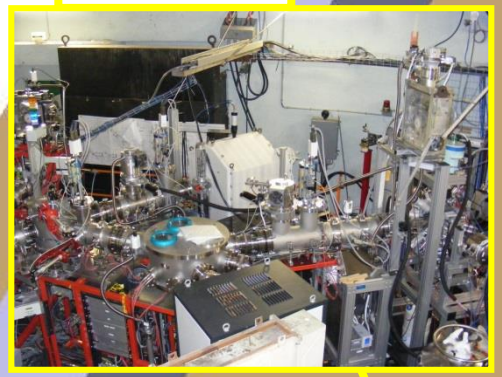


Tandem building
Institut de Physique Nucléaire
Campus of the Paris Sud University Orsay (France)

Beams available today at ALTO – 0.5 kW primary e-beam

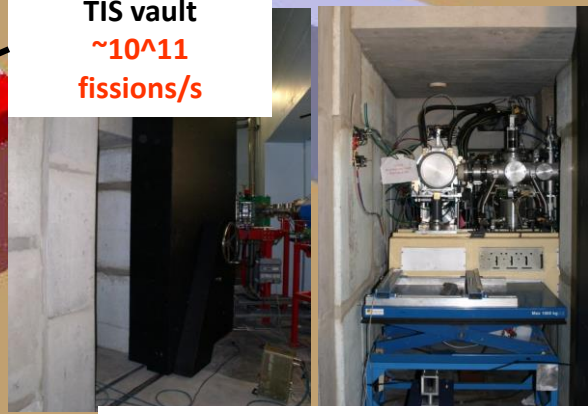
e-LINAC
10 µA 50MeV
0.5 kW
(former 1st section of the CERN LEP injector)

beta decay spectroscopy



Hall 110
experimental setups

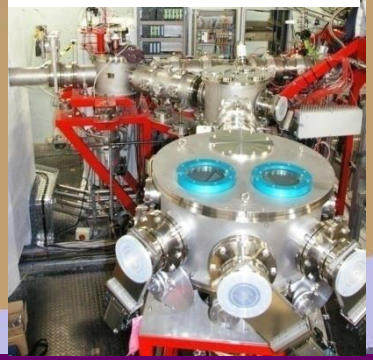
TIS vault
~10^11 fissions/s



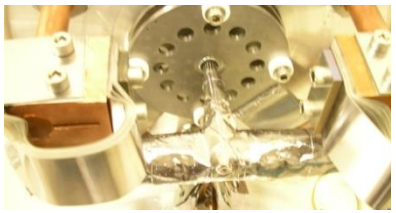
PARRNe
mass separator

secondary beam lines

kicker - bender



Target Ion-source ensemble
(30 keV ex)



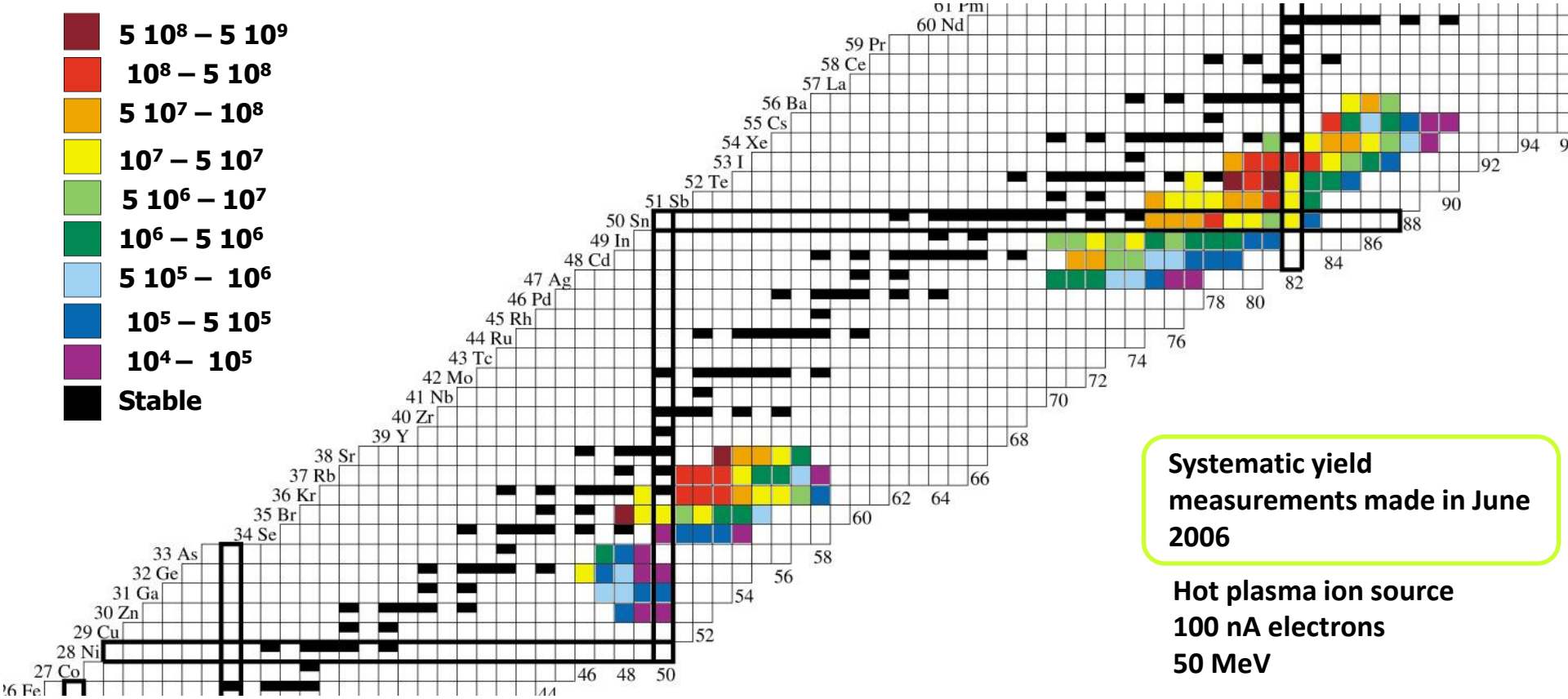
Beams available today at ALTO

Measured productions yields at the detection point on line with the PARRNe mass separator
electrons -> gamma induced fission

nominal intensity:
10 µA ⇒~ 10^{11} fissions/s

Production pps /10 µA e-

- **5 10^8 – 5 10^9**
- **10^8 – 5 10^8**
- **5 10^7 – 10^8**
- **10^7 – 5 10^7**
- **5 10^6 – 10^7**
- **10^6 – 5 10^6**
- **5 10^5 – 10^6**
- **10^5 – 5 10^5**
- **10^4 – 10^5**
- **Stable**



Systematic yield measurements made in June 2006

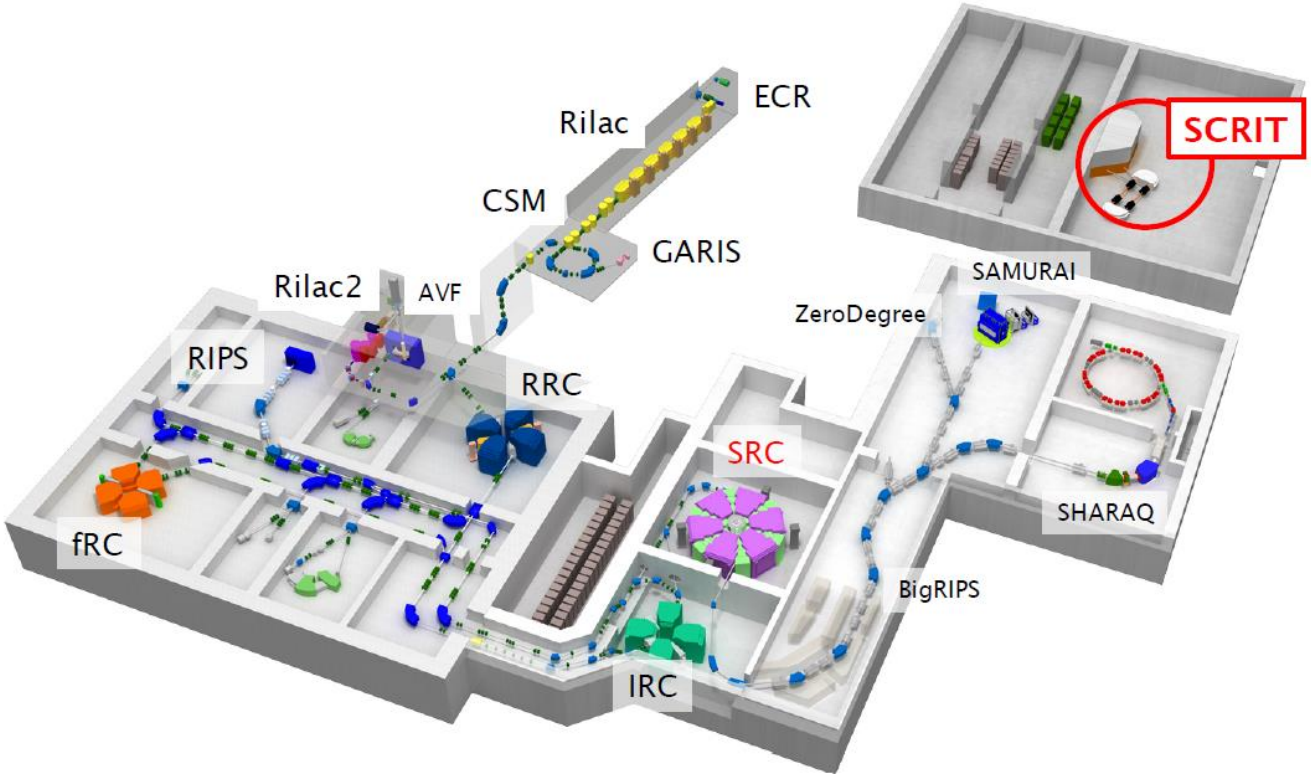
Hot plasma ion source
100 nA electrons
50 MeV

The SCRIT (Self-Confining Radioactive Ion Target) example

T. Suda, M. Wakasugi, T. Emoto, K. Ishii, S. Ito, K. Kurita, A. Kuwajima, A. Noda, T. Shirai, T. Tamae, H. Tongu, S. War and Y. Yano,
"First Demonstration of Electron Scattering Using a Novel Target Developed for Short-Lived Nuclei,"
Physical Review Letters **102** (10) (2009).

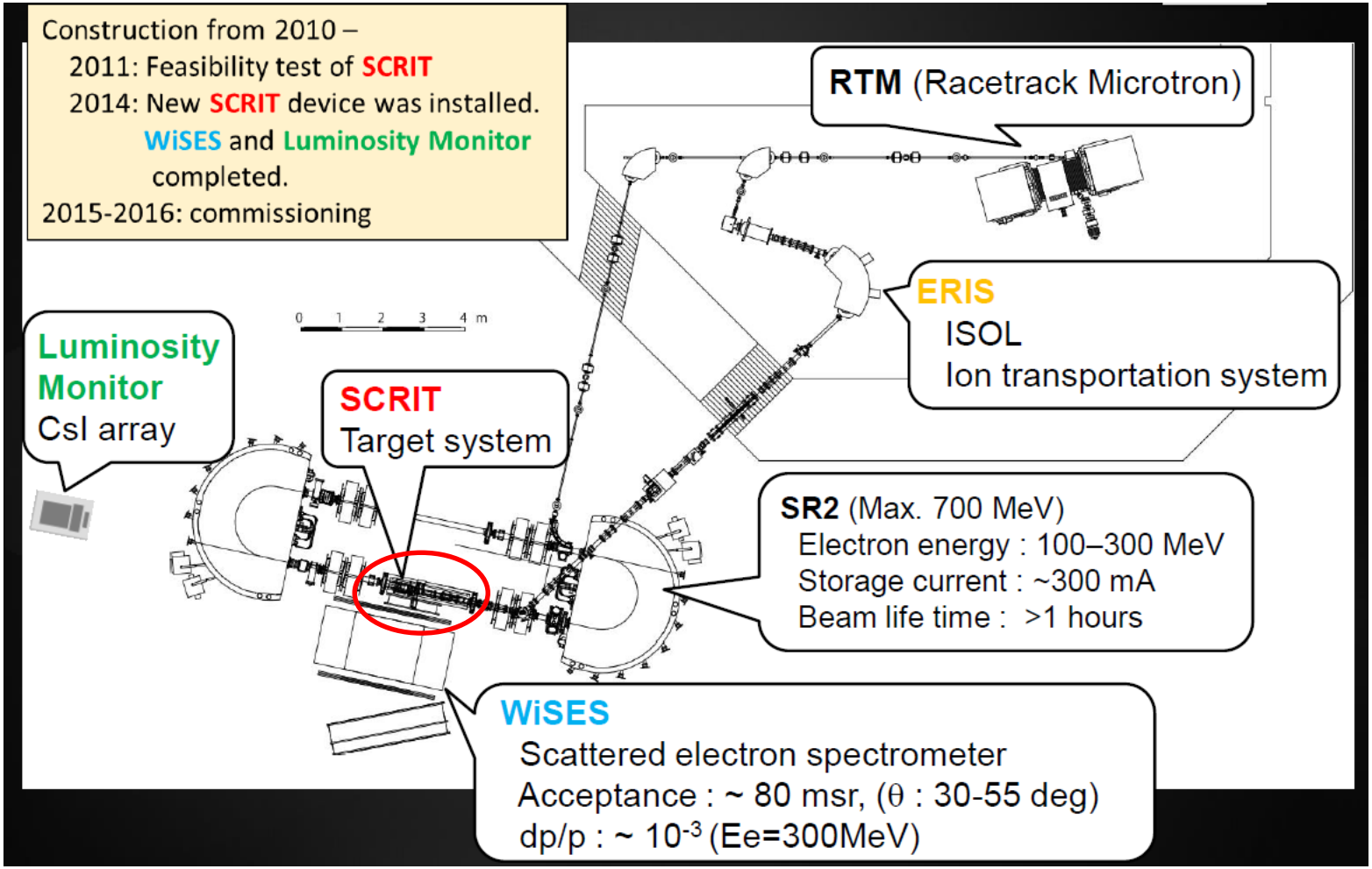
M. Wakasugi, T. Emoto, Y. Furukawa, K. Ishii, S. Ito, T. Koseki, K. Kurita, A. Kuwajima, T. Masuda, A. Morikawa, M. Nakamura, A. Noda, T. Ohnishi, T. Shirai, T. Suda, H. Takeda, T. Tamae, H. Tongu, S. Wang, and Y. Yano,
"Novel internal target for electron scattering off unstable nuclei,"
Physical Review Letters **100** (16) (2008).

Location of the SCRIT Facility in the RIKEN RI Beam Factory



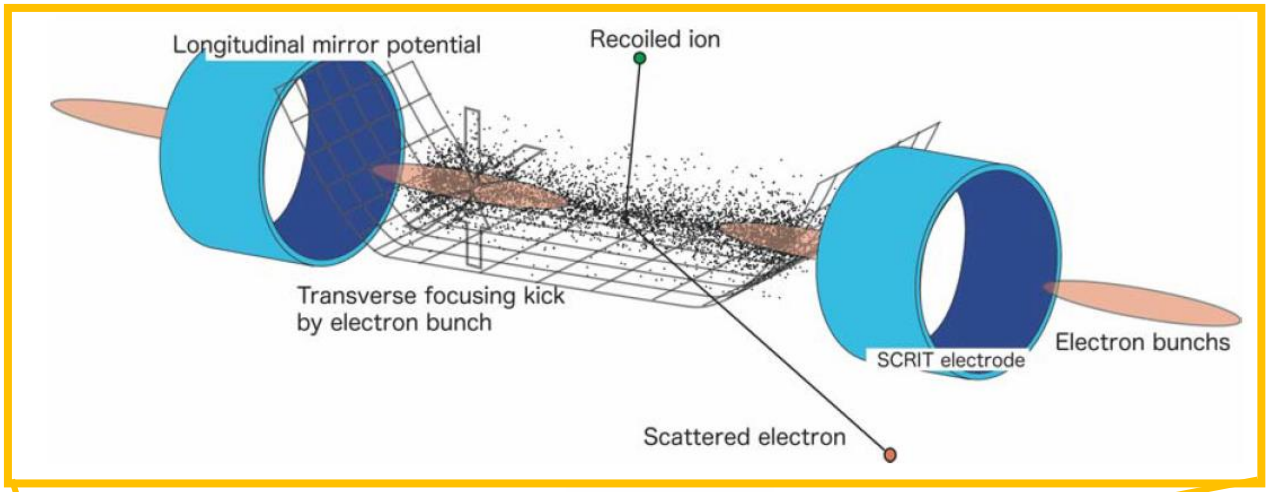
taken from : M. Wakasugi
Workshop on e-Ion collision
at CEA Saclay
(25-27 Apr. 2016)

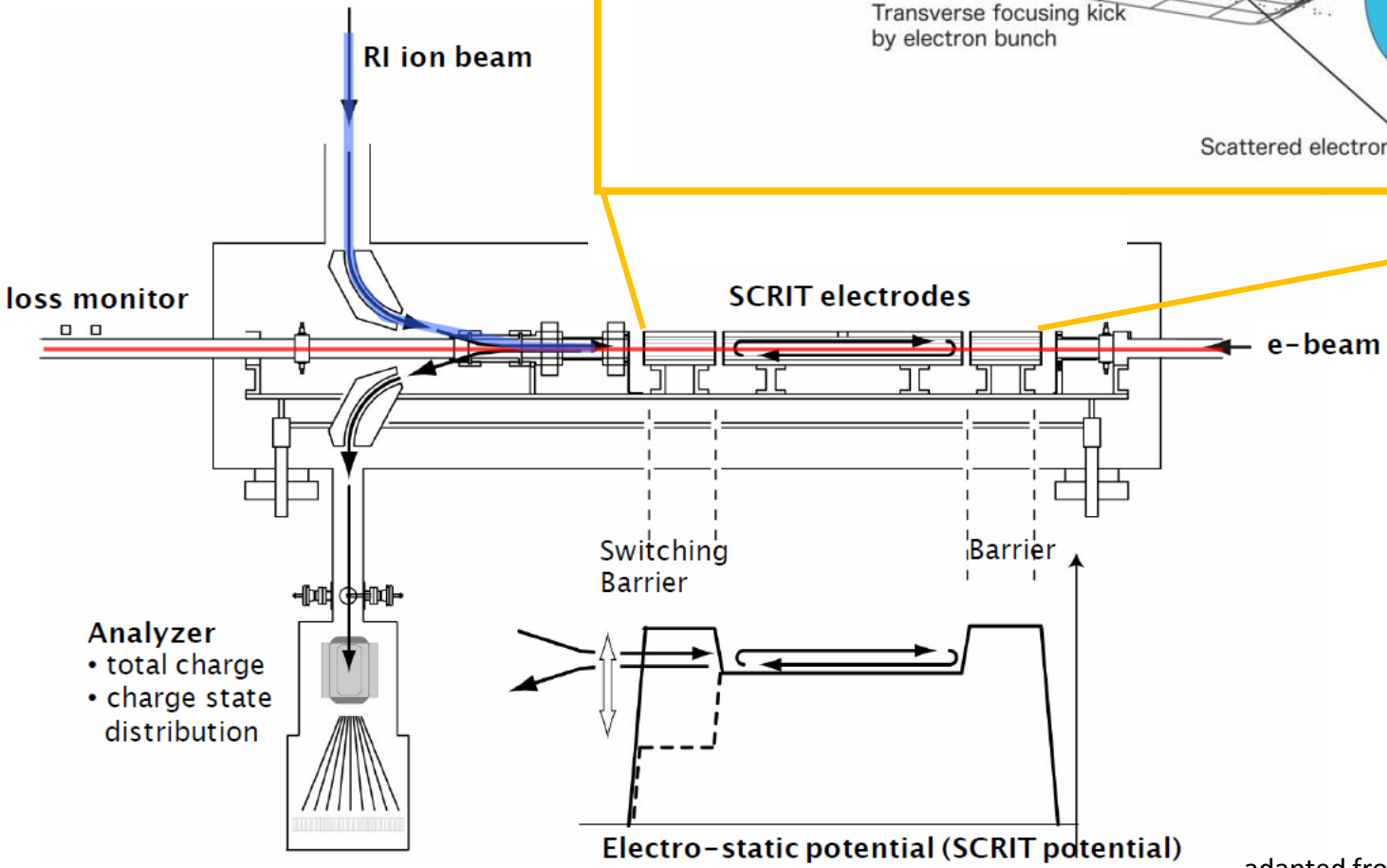
The SCRIT (Self-Confining Radioactive Ion Target) example



taken from : T. Tsukuda
Workshop on e-Ion collision
at CEA Saclay
(25-27 Apr. 2016)

The SCRIT (Self-Confining Radioactive Ion Target) example





adapted from : M. Wakasugi
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The SCRIT (Self-Confining Radioactive Ion Target) example

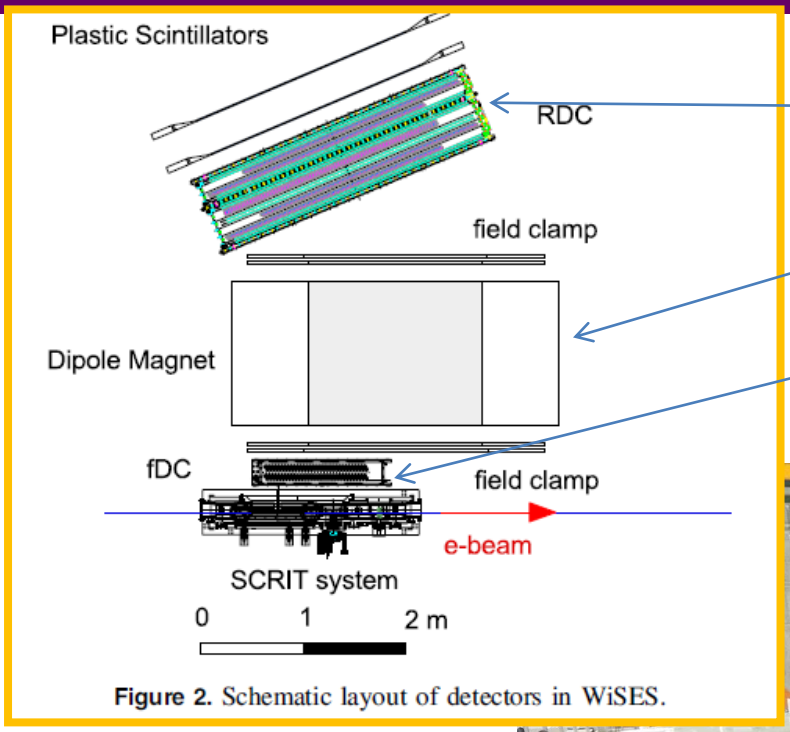
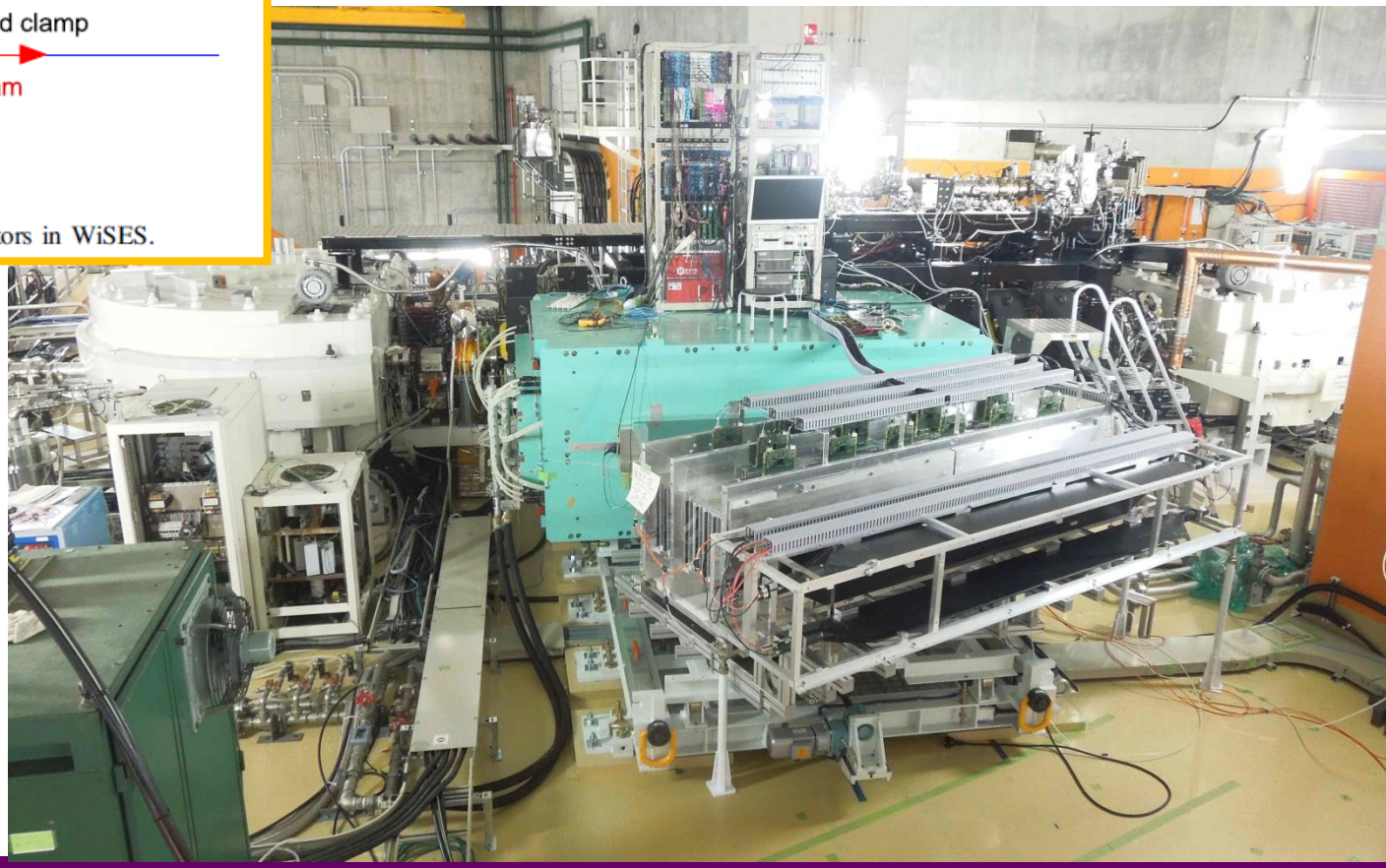


Figure 2. Schematic layout of detectors in WiSES.

Rear drift chamber

Dipole : 0.4 T for 150 MeV

Front drift chamber



T Ohnishi et al
Phys. Scr. T166 (2015) 014071

SCRIT@PERLE (@Orsay) ?

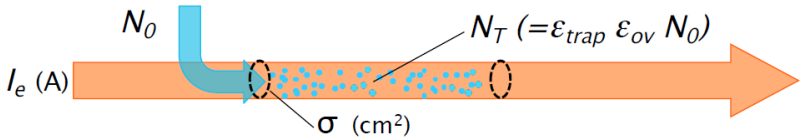
Chancé et al (CEA Saclay) ETIC project within GANIL-2025 (2015)
calculations within ERL hypothesis :

I_e=200 mA N_A=10^6 trapped ions: $\mathcal{L} \simeq 10^{29}$ should be achieved

based on

[A.N. Antonov et al., Nucl. Instr. and Meth. A **637** 60 (2011)] ELISE project GSI

Achievable luminosity

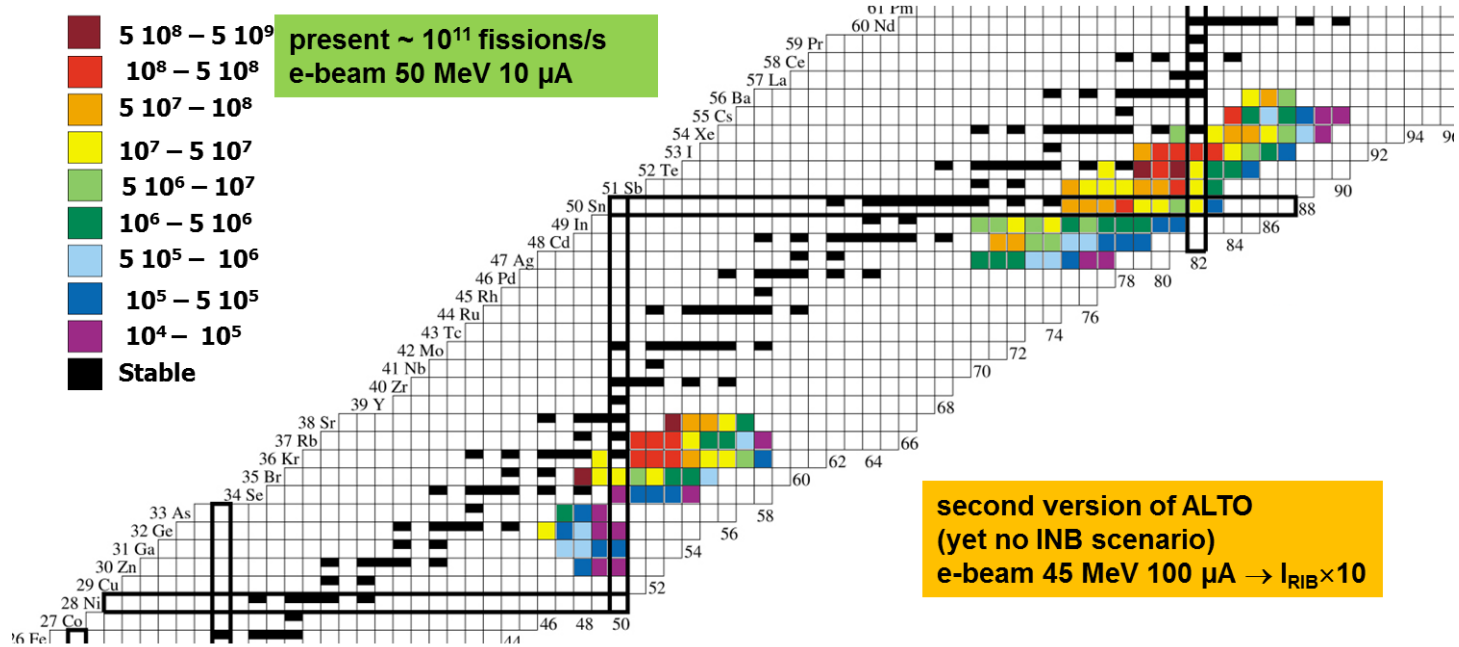


$$L \sim \frac{I_e/e \quad N_T}{\sigma} \ /(\mathrm{cm^2 s})$$

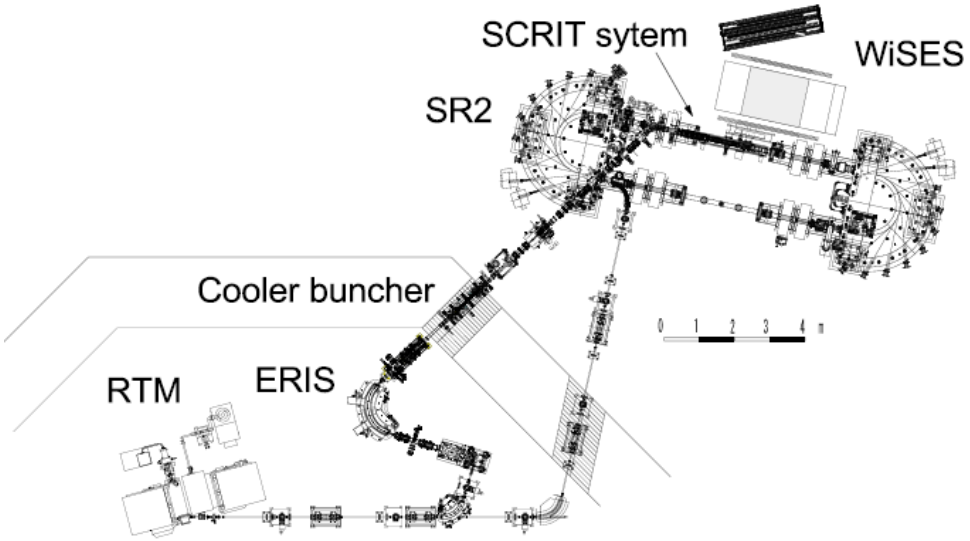
PERLE@Orsay : 20 mA $\rightarrow \mathcal{L} \simeq 10^{28}$ is *probably* achievable for a **10^6** trapped RI population **on the principle**

but the dynamical e-beam-RI coupling should be investigated : first time with a ERL time structure
e-beam instabilities ? impact on ERL operation ?

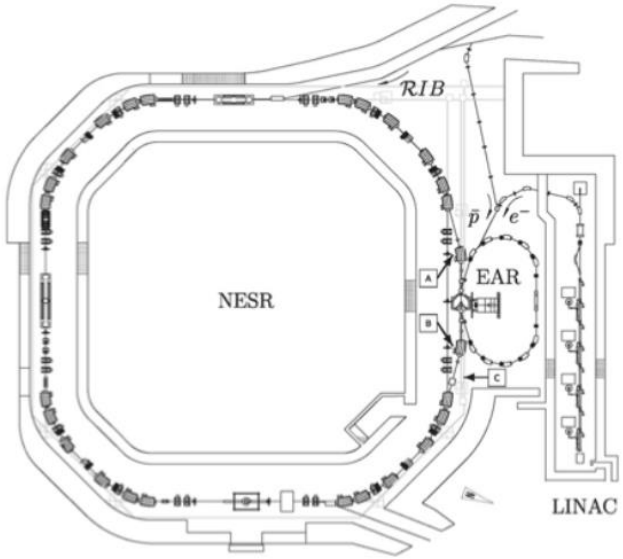
Production pps



International context/competition



SCRIT @ RIKEN
present luminosity limitations (10^{27})
RI target Z diversity ?



ELISE @ FAIR
not funded yet (if ever?)

Storage ring at HIE-ISOLDE
abandoned

ETIC proposal within GANIL2025
not retained

At Orsay : long, well established know-how on:
- electron acceleration
- electron detection
- Radioactive Ion Beam ISOL-production
- Radioactive Ion Beam manipulation & trapping

and a large nuclear physics users community!

So… what are we waiting for ?

thank you for your attention